METHOD AND APPARATUS FOR DRIVING TWO-DIMENSIONAL

MODULATOR ARRAYS

Inventors: Douglas A. Webb and Stephen Gaalema

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CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. Provisional Application Number 60/458,760, entitled "Method and apparatus for driving two-dimensional modulator arrays," filed March 28, 2003 by inventors Douglas A. Webb and Stephen Gaalema. The disclosure of U.S. Provisional Application No. 60/458,760 is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

1.   Field Of The Invention

The present invention relates generally to micro electromechanical systems (MEMS) and, more particularly, to circuits and methods for controlling a voltage in MEMS cells.

2.   Description Of The Background Art

A MEMS or micro electromechanical (MEM) device typically includes micromechanical structures or light modulating elements that may be actuated using electrical signals. The light-modulating elements may comprise, for example, Grating Light Valve™ (GLV™) light modulating elements available from Silicon Light Machines, Sunnyvale, CA (GLV™ and Grating Light Valve™ are trademarks of Silicon Light Machines). A light modulator may include an array of moveable structures referred to

as "ribbons." Light modulators may be used in various applications, including video, printing, optical switching, and maskless lithography, as just a few general examples.

Lithography and imaging applications using MEMS devices often require very large numbers of pixels to achieve high data rates. In some applications, a two-dimensional array of pixels may be required and the total number of pixels is typically too high to allow for individual MEMS cell driving control. That is, for a large two-dimensional array, each MEMS cell typically does not have its own dedicated driver circuit. Instead, row drivers, including driver circuits for each row, and column, including access circuits for each column, are used to control the MEMS cells. Such an arrangement **100** is shown in FIG. 1. The row drivers **102** deliver the stimulation signal for a given row of elements and the column drivers **104** are used to select the correct row stimulation for a given column. By using both together, all elements (MEMS cells **106**) may be driven with the desired stimulation in turn.

The MEMS cells **106** can include light modulators organized as "pixels." These pixels can require precise analog control for providing gray scale at an image target. In some applications, these MEMS arrays use pulsed laser sources on the surface of the modulator. Accordingly, the MEMS device would only need to be at an intended voltage state for a relatively short period of time.

FIG. 2 is a schematic diagram of a conventional MEMS driver circuit **200** that can be used with the array **100** shown in FIG. 1. This example uses a sample and hold circuit at each cell with sampling of the row analog data at each column in turn. Typically, this approach would require a high voltage sample and hold or a low voltage

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one with an amplifier on the output stage. In FIG. 2, a digital-to-analog (DAC) **202** drives a signal to a receiver **204** on the MEMS die **201**. The output of the receiver **204** can be the row drive signal **206** and it can connect to a column select switch **208**. Capacitor C1 can connect to the output of the column switch **208** and to the input of amplifier OP **210**. The output of OP **210** can connect to a transfer switch **212**. Capacitor C2 can connect to the transfer switch **212** and to a high voltage (HV) driver section. The HV driver section can include a resistor R2 connected between a high-voltage supply (HV supply) **214** and the MEMS cell **106** via the MEMS node **216**. Transistors Q1 and Q2, along with resistor R3 and voltage source V1 can be used to generate the current needed to produce a voltage across R2 complete the HV driver section. The circuit **200** allows for a voltage range of between about 3V and about 18V at the MEMS node **216** of the cell **106**.

SUMMARY

In one embodiment, a micro electromechanical system (MEMS) driver circuit receives a pulse-width modulated (PWM) signal and uses it to control a voltage at a MEMS cell. The driver circuit further includes a current source, a capacitor, and a reset circuit that can discharge the capacitor. The voltage at the MEMS cell can be controlled in proportion to the pulse width of the PWM signal.

In another embodiment, a MEMS driver circuit receives a first PWM signal and a second PWM signal. Each PWM signal is coupled to a current source. One current source can provide a course current control and the other current source can provide

fine current control. The driver circuit can further include a capacitor and a reset circuit for discharging the capacitor. The voltage at the MEMS cell can be controlled in proportion to a summation of the first and second current sources.

According to another aspect of the embodiments, a method of controlling a voltage at a MEMS cell is disclosed. The method includes the steps of receiving a PWM signal, controlling a current source with the PWM signal, and adjusting the voltage at the MEMS cell in proportion to a pulse width of the PWM signal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a conventional MEMS array including row and column drivers.

FIG. 2 is a schematic diagram of a conventional MEMS driver circuit.

FIG. 3 is a schematic diagram of a MEMS driver circuit according to an embodiment.

FIG. 4 is a schematic diagram of an example implementation of the MEMS driver circuit according to the embodiment of FIG. 3.

FIG. 5 is a simulation schematic diagram of a MEMS driver circuit according to the circuit of FIG. 4.

FIG. 6 is a timing diagram showing simulation results for the simulation schematic of FIG. 5.

FIG. 7 is a diagram showing the drive output versus the pulse width for the simulation schematic of FIG. 5.

FIG. 8 is a schematic diagram of a two-stage MEMS driver circuit according to an embodiment.

FIG. 9 is a signal diagram showing a multi-level signal approach applicable to a circuit according to an embodiment.

FIG. 10 is a schematic diagram of a two-PWM signal MEMS driver circuit according to an embodiment.

DETAILED DESCRIPTION

The approach discussed above in the Background section has several disadvantages, including circuit complexity, cross-talk resulting from driving a sensitive analog signal at high speed onto the MEMS die and then across the array, and data-dependent errors resulting from voltage drops across the MEMS die. What is needed is an approach that overcomes these limitations in controlling a two-dimensional array of MEMS cells.

Described herein are embodiments suitable for controlling MEMS devices and other applications that may include light modulators and devices. According to embodiments, amplitude information is brought onto the MEMS die or chip in digital form, as a pulse-width modulated (PWM) signal. This can eliminate the need to bring sensitive analog signals onto and across the chip and it may reduce the need for a large

device pin count, as may typically be required for parallel digital data interfaces. The PWM signal can be received and reshaped, including by any necessary level-shifting for voltage level compatibility, at the chip boundary. This approach can essentially eliminate the majority of the effects of noise and cross-talk, as described above.

Referring to FIG. 3, in each MEMS cell **106**, the PWM signal **302** corresponding to that cell **106** can be selected by the column select line **208**. Thus, the signals remain essentially digital in nature until the final stage where it can be converted to a current and used to charge a hold capacitor **304**. The "MEMS Node" **216** can connect to a movable structure (e.g., a ribbon in a particular example MEMS device) in a MEMS cell **106**. The voltage at the MEMS node **216** can be directly proportional to the pulse width of the PWM signal **302**. Accordingly, the digital pulse width of the PWM signal **302** can be used to control a voltage level, such as the MEMS node **216** at the MEMS cell **106**. This can then control a modulating effect on light impinging on the MEMS cell **106**. Each hold capacitor **304** in each row can be charged in turn to the desired level. In this one hold capacitor approach, the MEMS cells **106** can be brought to a desired state in sequential fashion and not all at the same time. This method may be ideal for a pulsed illumination source on the MEMS where the state of a MEMS cell **106** need only be "correct" or in a targeted state for a relatively short period of time. However, this approach could also be used for other types of illumination sources.

Referring again to FIG. 3, a schematic diagram of a MEMS driver circuit **300** according to an embodiment is shown. Of course, one skilled in the art would recognize a number of different ways to implement a driver circuit according to the teachings of

this embodiment. For example, the current source **308** can be implemented as a transistor operating in saturation mode. The reset switch circuit **310** can be a transistor or any other element or circuit that can implement a switching function. The buffer stage **312** accepting the PWM signal and providing a row drive signal can include voltage level shifting or translation circuitry as well as signal strength boosting circuitry, for example. Also, as will be described below, a high voltage stage can be included with at least 3 transistors per MEMS cell to implement these functions. Also, the logic circuit **314** receiving the column select signal can be implemented in any number of ways, including, but not limited to pass gate logic or other logic functions or circuits.

FIG. 4 is a schematic diagram of an example implementation **400** of the MEMS driver circuit **300** according to the embodiment of FIG. 3. The high voltage transistor "NMOS" **402** can be used to isolate the current source **308** from the high voltage seen at the output **216**. In one particular example, the voltage at the MEMS node **216** can range as high as about 25V. In this circuit **400**, a global reset function can be accomplished by turning all of the PWM drivers on (i.e., all PWM signals can go high), turning all of the column select signals **208** on and bringing the high voltage pulse (Hvpulse) signal **404** to ground. The current source transistor **308** can then discharge the hold capacitor **304** and the MEMS node **216** can also be discharged to ground.

FIG. 5 shows a simulation schematic diagram **500** of a MEMS driver circuit **400** according to the circuit of FIG. 4. That is, the circuit **400** of FIG. 4 can be modified in order to facilitate circuit simulation. FIG. 6 includes timing diagrams showing simulation results for the simulation schematic of FIG. 5. In FIG. 5, the "AND" function **314** is

implemented using two series transistors: one transistor **502** for the column select and one transistor **504** (in saturation mode) for the current source **308**.

The simulation was done in order to simulate a MEMS cell **106** where the pulse width of the PWM signal **302** is varied. The results of the simulation is shown in FIG. 6, where different symbols represent different experiments. In FIG. 6, the top (first) graph **602** shows the column select signal, with the first high pulse enabling the PWM signal **302** to pass through for the particular cell and the second pulse enabling a reset function. The second graph **604** shows a PWM signal **302** with high pulses varied from 0ns to 30ns during the column enable period. The PWM signal **302** is then held in a high state for the reset function. The third graph **606** shows the "HV" (high voltage) signal **404** changing from 0V to 25V. HV **404** is then discharged to 0V for the reset function. The bottom (fourth) graph **608** shows the voltage generated at the MEMS node **216** (shown as a "V" probe in the simulation schematic of FIG. 5). The superimposed graphs show the various voltage levels set on this node during the column enable period. These levels are in proportion to the pulse widths of the PWM signals **302** allowed through during the column enable period. The levels at the MEMS node **216** are then maintained after the column enable signal **208** goes low by the holding capacitor C1, which is a 50fF capacitor in FIG. 5. As HV **404** is discharged prior to the reset, all voltage levels in the fourth graph are brought down. Upon the reset function, all of these levels are brought to about 0V.

FIG. 7 shows the drive output **704** versus pulse width **702** for the simulation schematic of FIG. 5. The x-axis shows pulse widths **702** for the PWM signal **302**

increasing from about 0ns to about 30ns. The y-axis shows the voltage level, such as on "MEMS Node" **216** decreasing from about 24V to about 2V in a linear relation. This represents an example relation of the pulse width of the PWM signal **302** to the MEMS node voltage level **216**.

In some applications, the light source (e.g., LASER) used to impinge light onto the MEMS cells **106** may be of the continuous wave (CW) type. For this type of light source, the driver outputs corresponding to each MEMS cell **106** must change its state at substantially the same time, so there is a continuous resultant effect from the modulated light. For such an application, a two-stage MEMS driver circuit, such as the example circuit **800** shown in FIG. 8 may be a preferred solution. The first stage **802** can be essentially the same as the single-stage PWM controlled sample and hold circuit as described above for FIG. 3. The second stage can include operational amplifier OP **804** or any suitable circuit stage isolation structure, a transfer switch **806**, and a second hold capacitor C2 **808**. The last portion of the circuit of FIG. 8 (i.e. HV supply **214**, R1, Q1, Q2, R2, and V1) that directly drives the MEMS node **216** can be essentially the same as that in the conventional HV drive structure **200** described above with reference to FIG. 2. Returning to FIG. 8, the second stage, including the transfer switch **806**, which may include any suitable switching element, can function as a synchronization stage. When the "Transfer" signal is active, the entire image as modulated from the MEMS cells **106** on the device can be updated at essentially the same time. So, the entire image may effectively be updated at each MEMS cell **106** simultaneously in response to the transfer signal activation.

Another approach that can reduce the speed at which the PWM signal needs to be generated to produce a desired range and/or resolution of MEMS node **216** voltage levels includes the multi-level signal approach **900** shown in FIG. 9. In one example, a MEMS device may have 100 columns with each modulated at a rate of about 100 kilopixels/second. In this case, each column may need to be written in 100 ns (nanoseconds). If a desired resolution is 256 gray levels, the PWM generator would need to operate at a minimum rate of about 2.56GHz. Accordingly, a multi-level signaling approach may be useful for such an application. Such an approach may include first **902** and second **904** thresholds for the input signal **906** level that may correspond to control of a two current source driver circuit.

Referring to FIG. 10, a schematic diagram of a two-PWM signal MEMS driver circuit **1000** according to an embodiment, and can be built with either separate PWM signals or multi-level signaling approach **900**. This circuit **1000** can be used to allow for reduced speed requirements of the input signal **906** by including a coarse current source **1014** and a fine current source **1016** for each cell **106**. The hold capacitor **304** and reset circuitry **310** portions can be similar to those described above with reference to FIG. 3. In FIG. 10, a PWM "course" signal **1002** and a PWM "fine" signal **1004** can be received. Each can be received by a corresponding buffer circuit (**1006** and **1008**, respectively) and then input to a corresponding logic circuit (**1010** and **1012**, respectively). In this example, the column select signal **208** can connect to "AND" type gates of said logic circuitry to provide control for a course current source **1014** and a

fine current source **1016**. The sum of these two current sources can then be used to charge the hold capacitor **304** and to generate the voltage at the MEMS node **216**.

Referring back to FIG. 9, when the input signal level **906** starts below the first threshold level **902**, then both coarse and fine current sources would be off **910**, resulting in a low integrator output level **908**. When the input signal level **906** rises to be above the second threshold level **904**, then both coarse and fine current sources would be turned on **912**, resulting in a relatively rapidly rising integrator output level **908**. When the input signal level **906** is reduced such that it is below the second threshold level **904** but above the first threshold level **902**, then only the fine current source **1016** would be turned on **914**, resulting in a relatively slowly rising integrator output level **908**. Finally, when the input signal level **906** is reduced such that it is below the first threshold level **902**, then both current sources would be turned off **916**, resulting in a steady integrator output level **908**.

This concept can also be extended to three or more current sources. In principal, for example, two 16-level PWM signals could produce 256 gray scales, reducing the PWM generator clock rate to about 160MHz. In some cases, matching current sources to be exactly a ratio of 16-to-1 may be a particular challenge. One way to compensate for some inaccuracies in the ratio may be to provide more precision in the PWM signal. For example, the fine control may include 32 levels instead of 16 levels.

Note that the PWM signals, as described above with reference to the embodiments may be included on the same physical die or integrated circuit with the MEMS structures, or they could alternatively be implemented as a separate chip.

While specific embodiments of the present invention have been provided, it is to be understood that these embodiments are for illustration purposes and not limiting. Many additional embodiments will be apparent to persons of ordinary skill in the art reading this disclosure.